Development of a Double-Pass Thomson Scattering System in the TST-2 Spherical Tokamak

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A double-pass Thomson scattering system, in which a laser pulse makes a round trip through the plasma, was constructed. Using the same optics and a fast detection unit, we can resolve backward and forward scattering pulses in the signal. Because these scatterings reflect velocity distribution along different directions, electron temperature anisotropy can be estimated from the double-pass Thomson scattering system.

Keywords: Thomson scattering, temperature anisotropy, forward-backward scattering, multi-pass, TST-2

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Multi-pass Thomson scattering scheme is attractive for low-density plasma and electron temperature anisotropy measurements. A significant improvement in the signal-to-noise ratio was achieved using a multi-pass Thomson scattering scheme on TEXTOR [1]. However, it is difficult to apply a similar multi-pass system to other devices because of the use of the intra-cavity configuration. In contrast, the configuration using a confocal spherical mirror is simple. The theoretical performance of this system was analyzed and confirmed experimentally [2]. When the angle between $\overrightarrow{k_s} - \overrightarrow{k_i}$ and the toroidal field is far from 45°, the multi-pass configuration provides an opportunity for temperature anisotropy measurements. Bowden *et al*. measured temperature anisotropy using a single-pass Thomson scattering for electron-cyclotron-heated low-density plasmas ($T_e \sim 1$ eV and $n_e \sim 10^{17}$ m^{-3}) [3]. They switched the direction of the incident laser and measured reproducible plasmas. They detected slight temperature anisotropy. As a pilot experiment for the temperature anisotropy measurement, a double-pass Thomson scattering system was constructed in the Tokyo Spherical Tokamak 2 (TST-2) device. Combining the double-pass configuration with a fast detection system, we can measure the forward and backward scattering pulses almost simultaneously (i.e., within a time separation of 20-30 ns). Therefore, we can measure electron temperature anisotropy even if plasma reproducibility is poor. This is important when we study phenomena related to instabilities. In this paper, the double-pass Thomson scattering scheme is described and the experimental results are presented.

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In the Thomson scattering system in TST-2, the pulse energy, repetition rate, and pulse width of the injection Nd:YAG laser are 1.6 J, 10 Hz, and 10 ns, respectively. Newtonian collection optics allows for a large solid angle [4]. The polychromator has six wavelength channels, and each channel has a filter and an avalanche photodiode. Applying a long, large numerical-aperture fiber and a high-power injection laser, the signal intensity was enhanced significantly; maximum signal-to-noise ratio was more than 10 [5]. Only the data at the center of plasma are presented in this paper, because the stray light is extremely bright in other regions in the double-pass configuration. In order to distinguish pulses from each laser transit through the plasma, a fast low-noise detection system was developed, and the measured full width at half maximum of the laser pulse was approximately 10 ns [6]. A schematic diagram of the double-pass Thomson scattering system is shown in Fig. 1. Injected laser travels through the plasma and is reflected by a concave mirror. The scattering angles for the first and second pass are 120° and 60°, respectively, and the angles between the toroidal field and the injected laser for the first and second pass are 60° and 120°, respectively (Fig. 2). As a result, the electron temperature is measured perpendicular and parallel to the toroidal field from the first- and the second-pass, respectively.

The target plasma parameters are as follows: plasma current $I_p \sim 100$ kA, line average electron density $n_e l \sim 10^{19}$ m^{-2}, and toroidal field $B_t \sim 0.2$ T. Figure 3 shows a typical waveform of the double-pass Thomson scattering signal. Because the two peaks arising from the first and the second Thomson scattering overlap slightly, we fit the

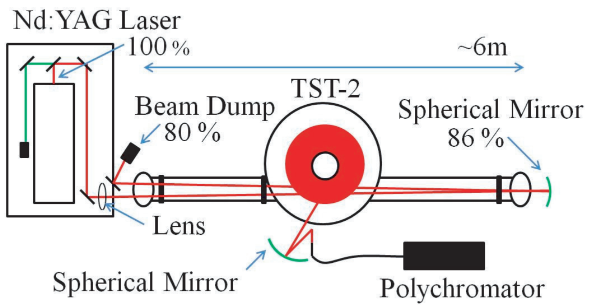

Fig. 1 Schematic diagram of the double-pass Thomson scattering system on TST-2.

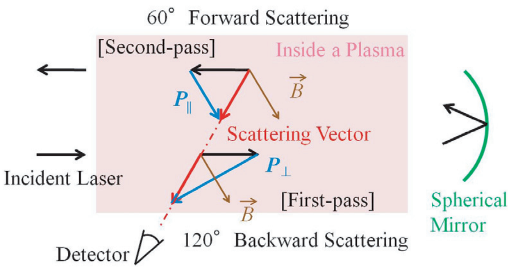

Fig. 2 Schematic diagram of temperature anisotropy measurement by double-pass Thomson scattering scheme on TST-2.

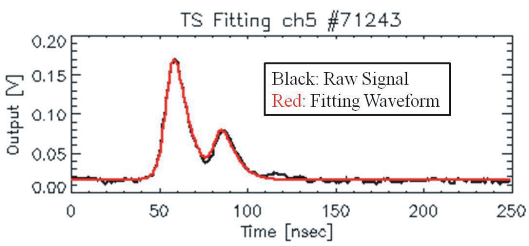

Fig. 3 Typical waveform of double-pass Thomson scattering measurement. The black line denotes the raw signal and the red line denotes waveform fitting.

measured waveform to a synthesized waveform consisting of two independent template waveforms f. The function f represents a single scattering pulse, which is obtained by averaging 28 pure single-pass Thomson scattering signals. The observed double-pass waveform (with two peaks) can be expressed as

$$y(t) = af(t - t_0) + bf(t - t_0 - t_{\mathrm{delay}}) + c. \quad (1)$$

Here, a and b represent the magnitude of the first and second scatterings, respectively. The parameter c specifies the background light from the plasma. The parameter t_0 specifies the timing of the first scattering and t_{delay} denotes a constant time delay between the first and second pass peaks. Using double-pass Thomson signal from six wavelength channels, $T_{\mathrm{e}\perp}$, $T_{\mathrm{e}\parallel}$, $n_{\mathrm{e,first}}$, and $n_{\mathrm{e,second}}$ were estimated. Figure 4 shows the result of fitting with two Maxwellian distribution functions at $T_{\mathrm{e}\perp} = 222 \pm 22$ eV and $T_{\mathrm{e}\parallel} = 213 \pm 25$ eV. Relative measurement errors were proportional to the summation of the photon noise and the circuit noise. The absolute value of the errors were adjusted so that $\chi^2 = n - m$, where $n - m = 4$ denotes the degree of freedom for the fitting. Figure 5 shows the relationship between $T_{\mathrm{e}\perp}$ and $T_{\mathrm{e}\parallel}$ for high density plasmas. The relative difference is $\left\langle \frac{T_{\mathrm{e}\perp} - T_{\mathrm{e}\parallel}}{T_{\mathrm{e}\perp}} \right\rangle = 3\% \pm 10\%$. When the plasma is in a banana region, $T_{\mathrm{e}\perp}$ can be higher than $T_{\mathrm{e}\parallel}$ in the high-field side and $T_{\mathrm{e}\parallel}$ can be higher than $T_{\mathrm{e}\perp}$ in the low-field side. However, such an effect is weak and the plasma should be isotropic near the magnetic axis; the data from this region were analyzed in this paper. To examine off-axis temperature anisotropy, we are preparing for a multi-point Thomson scattering system.

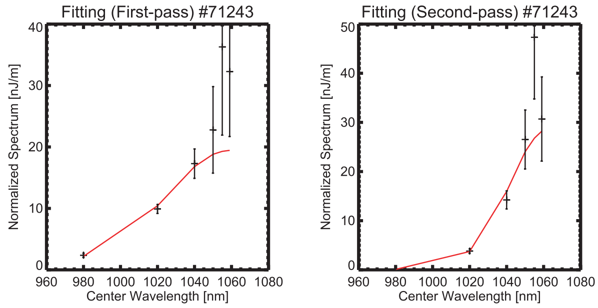

Fig. 4 Result of fitting of first- and second-pass signals to the Thomson spectrum. + denotes the measured value and the red line denotes the fitting result. The error bars are plotted. Each wavelength signal is normalized by its wavelength-integrated responsivity.

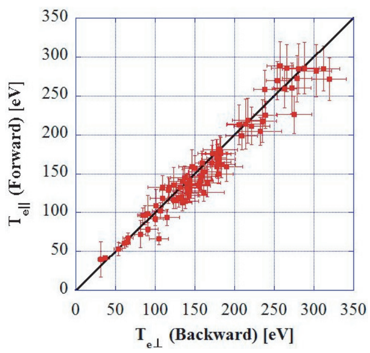

Fig. 5 Relationship between $T_{\mathrm{e}\perp}$ and $T_{\mathrm{e}\parallel}$ for high-density plasmas.

In summary, a double-pass Thomson scattering system was constructed on TST-2 and two Thomson scattering pulses corresponding to the first and second pass were clearly obtained. $T_{\mathrm{e}\parallel} \sim T_{\mathrm{e}\perp}$ within the experimental margin of error for most of the data.

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